High resolution long term morphological model of the northern part of the Holland Coast and Texel Inlet

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ABSTRACT: A high resolution morphological model of the northern part of the Holland Coast and Texel inlet is presented in this paper. The model includes the morphological effects of the combined action of tides and waves and focuses on the long term morphology (decades) that is dominated by the longshore coastal processes. This model has been set up and calibrated on observed morphological developments, and then applied to future development schemes. It was concluded that the model produces reliable results, making it a useful tool for decision making processes.

1 INTRODUCTION

The central part of the Dutch North Sea coast – the Holland coast - is characterized by sandy beaches and dunes, partly defended by low crested beachheads at typical intervals of 200 - 300m. In spite of these beachheads, the sandy coast is subject to erosion, and regular beach nourishments are required to keep the safety level of the sea defense to standard. The erosion processes at the beach are mainly wave driven (van Rijn, 1997).

To the north the coast is interrupted by a series of tidal inlets, the first being the inlet of Texel Island. At this inlet a net influx of sediment from the sea into the inlet of several millions of m^3 per annum occurs. This influx is mainly tide driven (Elias, 2006).

The combined action of wave driven beach erosion and tide driven influx through the inlet result in a complex dynamic morphological system, and a significant loss of sediment in the coastal zone.

To safeguard the stability of the sea defense on the long run, and to combat the ongoing loss of sediment in the foreshore, the Dutch government is investigating options for improvement. To support the evaluation of these technical options morphological models are used. In the past Elias (2006) has set up a sediment transport model of the ebb tidal delta, but no morphological changes were calculated. In this paper a new high resolution process based morphological model called FINEL2d is presented which is set up and calibrated for this area. This model combines the wave dominated coastal processes and the tide dominated ebb tidal delta. After calibration, the model is used to determine the morphological impacts of several measures. The time horizon of the morphological computations is 50 years. Examples of measures are: implementation of shore face nourishments, removal of the beachheads and construction of beach expansions.

The content of this paper is as follows: In section 2 the area of interest in introduced. Section 3 describes the FINEL2d model. The model set up and calibration is described in section 4. Section 5 describes the morphodynamic results. Finally in section 6 conclusions are given.

2 THE NORTHERN PART OF THE HOLLAND COAST AND TEXEL INLET

2.1 *Study area*

The study area extends from the coast at Camperduin to the Island of Texel, the ebb tidal delta and the western part of the Waddensea (see Figure 1). The coastal part of the main land is approximately 25 km long. Tidal ranges in this area are 1m during neap tide and 2m during spring tide. The mean significant wave height is 1.3m (Elias, 2006). Tidal ebb and flood velocities range between 1.0 and 2.0m/s in the Texel inlet (Ridderinkhof et al., 2002). Most of the sediment consists of a typical size of around 200μm.

2.2 *Main land coast*

The coast south of Camperduin is characterized by a sandy beach. Beach nourishments are necessary to compensate beach erosion due to longshore gradients. At this coast section some low crested beachheads are present.

Between the towns of Camperduin and Petten (see Figure 1) a sea defense of approximately 6 km long was built in the 19th century to prevent flooding of the hinterland. The sea defense consists of a heavy revetment, with beachheads in front and is called the Hondsbossche and Pettemer sea defense. No sand nourishments take place here.

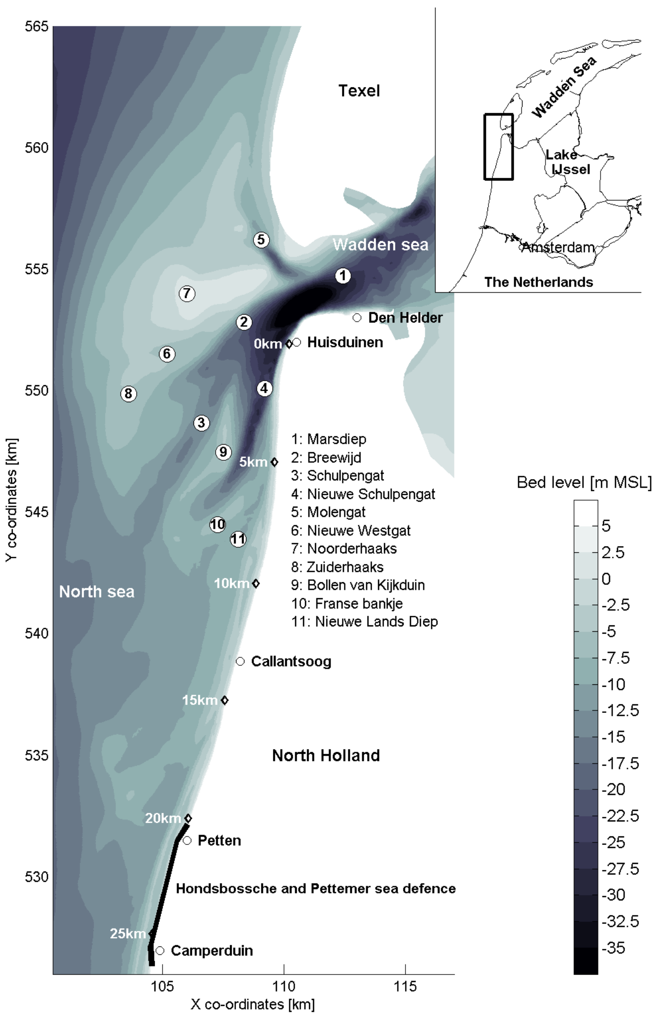

Figure 1. Overview of the study area

The sandy coast between Petten and Huisduinen is characterized by a transition of a fully wave dominated coastal beach system in the south to a coast which is highly influenced by the ebb tidal delta in the north. Waves coming from a northwest direction cannot penetrate to the beach in the north due to the presence of the shallow ebb tidal delta. Therefore the coast between Petten and Huisduinen is characterized by an increasing northward directed longshore sediment flux, due to the absence of southward directed waves. The net northward directed annual sediment transport is estimated at 0 m^3/year at 39km south of Huisduinen (not in figure) increasing to 200,000 m^3/year at Petten (20km from Huisduinen) and increasing further to 400,000 m^3/year at Huisduinen (0km) according to Van de Rest (2004). The work done by Van de Rest is based on Van Rijn (1997). Here beach nourishments are also necessary to compensate beach erosion due to this gradient. At this coast section also some low crested beachheads are present. The beachheads of this coastal stretch (interspacing 200-300m, crossshore length about 100m) were originally designed to reduce the coastal erosion.

2.3 *Ebb tidal delta*

The ebb tidal delta of the Texel inlet has gone through large changes since the closure of the Zuiderzee (now Lake IJssel) in the 1930's (Elias, 2006). In the outer delta near Huisduinen an ebb tidal channel called Nieuwe Schulpengat (4) has formed (Figure 1) and this channel is (still) migrating to the coast. Together with the original Schulpengat (3) these two channels are the main channels in the ebb tidal delta and are directed southwards. Peat layers are present in and around the Nieuwe Schulpengat (4) which are slowing down the migration (Cleveringa & Elias, 2003), but the exact location of these layers is not known. A shoal called Noorderhaaks (7) is present between the large southward directed channels and the small northward directed channel called the Molengat (5). An old channel called Westgat (6), which has filled up over the last decades still can be seen in the geometry. The inlet itself is called Marsdiep (1) and also has peat layers, which makes it a fairly stable channel.

Sediment budget analysis of the ebb tidal delta shows that between 1925 and 2000 approximately 280 million m^3 sand has eroded, which is an average of 3.7 Mm^3 per year (Elias et al., 2006). The sediment responsible for this erosion originates from the area west of the Noorderhaaks (7) (see also Figure 3). This sand is for the largest part transported towards the Wadden Sea. Elias (2006) estimates the sediment import to the Western Wadden Sea at 5 – 6 million m^3 per year, but continuing measurements should enhance this estimate in the near future. This import is mainly due to morphological adaptation resulting from the closure of the Zuiderzee in the 1930's. This adaptation process is still going on.

2.4 *Beach nourishments*

Since 1990 the coast is kept in place at the position of the year 1990, which is referred to as the basic coastline, since then beach nourishments have kept the coastline at that position. The average nourishment requirement to maintain the coastline between Camperduin and Den Helder has been 460,000 m^3/year until 2000. In 2000 an additional policy has been applied to also maintain the volume of sand in the so called coastal foundation. This had led to increased nourishment volumes causing a seaward move of the coastline. For the natural erosion of the coast the figure of 460,000 m^3/year for this section of the coast seems reasonable given the estimations of the annual net longshore sediment transport in section 2.2. Along the sea defense between Camperduin and Petten no nourishment has taken place.

3 THE MORPHODYNAMIC MODEL FINEL2D

3.1 *General*

The water flow, sediment transport and morphological changes are calculated using a model called FINEL2d. This is a 2DH numerical model based on the shallow water equations and is numerically solved by means of the finite element method. FINEL2d is developed by Svašek Hydraulics. The governing equations are described in Dam et al. (2007).
FINEL2d is coupled to the wave model SWAN to account for wave driven currents and the effects of waves on the shear stress, see section 3.2. The sediment transport module is described in section 3.3

3.2 *Wave model SWAN*

Waves play an important part in the morphological changes near the beach. For this reason the wave model SWAN is integrated into the model suite. See Booij et al., (1999) for a description of SWAN. The wave model SWAN is used in the model in 2 ways:

1. The spatial distribution of wave stresses is input for the hydrodynamic module to include the effect of wave driven currents in the total flow pattern. Because of the varying water level during the tide several updates are done during each tide. FINEL2d provides water levels and current fields to SWAN.
2. The spatial distribution of the wave orbital motion at the seabed (amplitude and direction), is used to account for wave related bed shear stress to obtain the total shear stress as input for the sediment transport module.

3.3 *Sediment transport module*

To determine the sediment fluxes the transport formula of Engelund & Hansen (1967) is used. The formula can be rewritten using:

$$\tau_{b,c} = \frac{\rho g u^2}{C^2} \qquad (1)$$

where $\tau_{b,c}$=shear stress due to current [N/m^2]; g = gravitational acceleration [m/s^2]; ρ=density of water [kg/m^3]; u =velocity [m/s]; C= Chézy value [$m^{0.5}$/s];

The effect of the stirring of the waves is included by introducing an extra wave shear stress term and rewriting the Engelund & Hansen formula according to:

$$q_{t,cw} = \frac{0.05\overline{u}^3}{(s-1)^2 g^{1.5} d_{50} C\rho}(\tau_{b,c} + \tau_{b,w}) \qquad (2)$$

where $q_{t,cw}$ = volumetric total load transport [m^2/s]; s= specific density [-]; d_{50} = median grain size [m]; $\tau_{b,w}$=shear stress due to waves [N/m^2].

It is assumed that the sediment transport is mainly suspended sediment transport. Therefore a time lag effect is introduced in the model according to Gallapatti & Vreugdenhil (1985).

4 MODEL SET UP

4.1 *Grid schematization and boundary conditions*

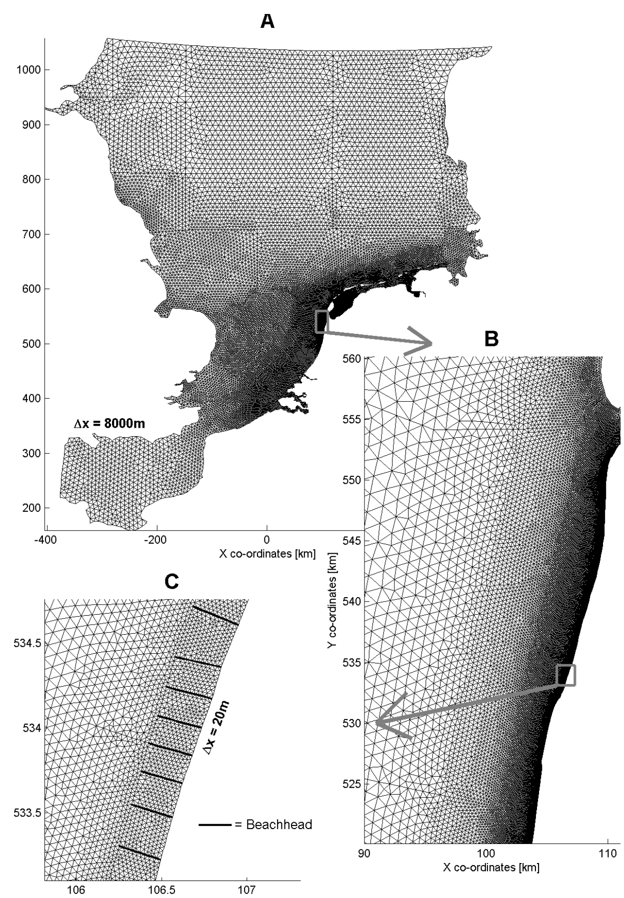

Figure 2. Grid schematisation from coarse (A) to fine (C)

FINEL2d uses unstructured triangular grids. The advantage of such meshes in comparison to for example finite difference grids is the flexible mesh generation. In this way no nesting techniques are required in regions of specific interest, where a

higher degree of resolution is needed, whereas arbitrary coastlines and complex geometries can be resolved very well.
The seaward boundaries of the computational mesh are chosen far away: in the English Channel in the south and along a line from England to Denmark in the north, see Figure 2a. These boundaries coincide with existing models and which can therefore be used to obtain the corresponding boundary conditions of the vertical tide. In this way a large part of the North Sea is covered by coarse grid cells, with only a limited impact on computational effort. Near the Holland coast the grid is gradually refined to a typical resolution of 20m at the beach (Figure 2c). The total number of grid cells is 139,400. Also visible in Figure 2c are the beachheads, which are incorporated in the grid. The resolution of the area between the beachheads is sufficient to account for eddies and complex currents.

4.2 *Wave climate*

Since the use of a morphological acceleration factor is required to keep the computational time within a reasonable time frame (Roelvink, 2006) the schematization of the wave climate is not straightforward. It is necessary to limit the number of wave conditions in such a way that the morphological effect is representative for the real wave climate.
For the definition of the representative wave conditions, the CERC formula (US Army Corps of Engineers, 1984) is used to assess the longshore transport rates for the years 2001 and 2002 using the statistical distribution of the observed offshore waves over these years. The waves are transferred to the beach on one point using the linear wave theory. The location of Petten is used to get this representative wave climate. The waves are then classified into 6 classes depending on the angle of the waves relative to the shoreline. Each class has a range of 30 degrees, covering the full directional distribution of the waves. So there are 3 classes for northern waves and 3 classes for southern waves, see Table 1. For each direction class the total transport rate over the full range of wave heights is calculated, again using the CERC formula. Finally, for each direction class a representative wave is defined that gives the same transport as the observed waves together, see Table 1. For high waves (h_s >2.4m) a separate analysis is performed for both the north and south going waves. The outcome is given in Table 1 as north storm and south storm.
The time at which a wave condition is enforced is rounded towards one tide or more, depending on the percentage of the occurrence of that wave class. So the wave occurs during both low tide and high tide and during ebb current and flood current. In this way a representative wave climate is defined, mixed in a representative way with all relevant tidal conditions. To get a full representative wave climate 56 tides are required, which are 2 neap-spring cycles (approximately 28 days). Using a morphological acceleration factor of 49.5 this corresponds to a 4 year period.

Table 1. Applied wave climate in the model

Wave	% time	tides	T	dir	h_s
	(%)	(-)	(s)	(°)	(m)
North 1	3.4 %	2	4.0s	-73°	1.1m
North 2	17.9 %	10	4.4s	-44°	1.4m
North 3	12.3 %	7	4.4s	-17°	1.3m
North storm	1.6 %	1	6.3s	-28°	2.9m
South 1	11.9 %	7	4.7s	15°	1.3m
South 2	18.0 %	10	4.8s	44°	1.2m
South 3	9.4 %	5	4.2s	73°	1.0m
South storm	1.7 %	1	6.3s	29°	3.2m
Calm	23.9 %	13	-	-	-
Total	**100.0 %**	**56**	**-**	**-**	**-**

T: mean wave period [s]; dir: wave direction relative to the shoreline [°]; h_s: significant wave height [m]

4.3 *Calibration of the water motion*

The first step in the calibration of a morphodynamic model is to calibrate the (tidal) water motion. In this model the water motion is calibrated on the astronomical M2 and M4 components of the vertical tide at several locations in the area of interest. Table 2 shows the difference between the observed and simulated amplitude and phase of the M2 and M4 components. As can be seen the model results are within acceptable accuracy ranges.

Table 2. Differences in amplitude and phase of the tidal components of M2 and M4 between observations and model

	M2	M2	M4	M4
Criterium	ampl (%) **(<6%)**	phase (˚) **(<10˚)**	ampl (%) **(<25%)**	phase (˚) **(<10˚)**
Location:				
Petten	5%	-6˚	-10%	-5˚
Den Helder	4%	-6˚	-10%	-8˚
Texel	4%	-5˚	-2%	-8˚

Buijsman & Ridderinkhof (2007) present M2 and M4 amplitudes of the discharge through Texel inlet, based on the period 1998 to 2002. Using the FINEL2d model we computed these amplitudes for the year 2000, including wind and barometric pressure effects. The results of the observed and model discharge at the Texel Inlet can be found in Table 3.

Table 3. Observed and computed M2 and M4 amplitudes of the water discharge of the Texel Inlet for the year 2000

	Observed	Model
	(m^3/s)	(m^3/s)
M2	65690	67260
M4	6750	5735
net	-560	-1103

As can be seen from Table 3 the observed discharge amplitudes can be calculated quite well for both the M2 and M4 component. The net water discharge is directed outward to the North Sea both in observations and model. The difference in the net discharge seems large, but is small compared to the total discharge.

4.4 *Calibration of the sedimentation/erosion pattern*

The morphological behavior of the model is calibrated on the period 2000 to 2006. The first part of the morphological calibration consists of the comparison between the observed erosion/sedimentation pattern (Figure 3) and the calculated pattern (Figure 4).

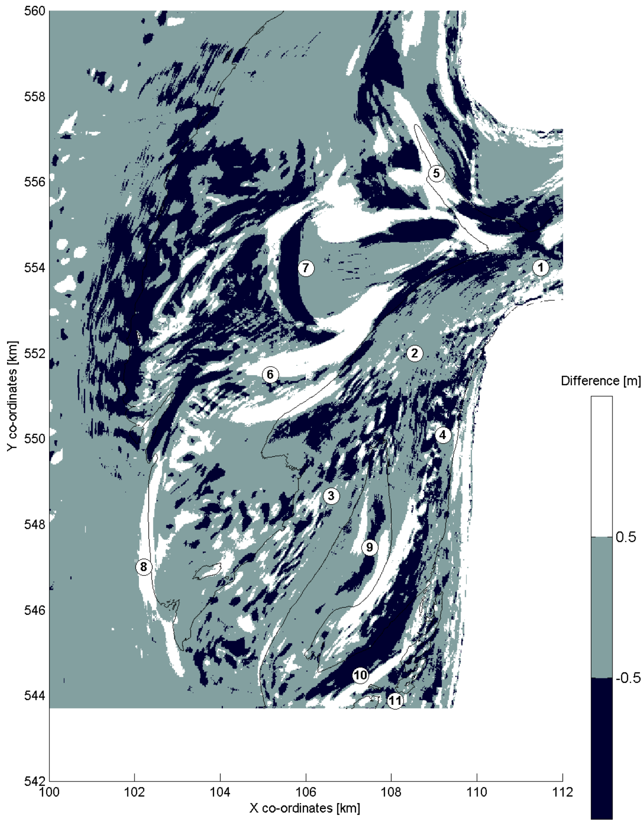

Figure 3. Observed erosion/sedimentation pattern 2000-2006

Several developments which have occurred in reality can be seen in the model. The sedimentation of the Nieuwe Westgat (6) is calculated correctly. The Molengat (5) shows a migration towards the coast both in the observations and the model. Also the expansion of the ebb tidal delta in southerly direction (8), south of the Zuiderhaaks, is calculated correctly, although the model is overestimating the sedimentation. The migration of the southern part of the Nieuwe Schulpengat (10) towards the coast is visible in the observations and also in the model. The large erosion just west of the shoal the Noorderhaaks (7) (X: 102km, Y: 553km) is not as large as in the observations. In the model there is a large erosion visible in the Breewijd channel (2) at the junction of the Schulpengat and the Nieuwe Schulpengat which is not visible in the observations. Presumably some erosion resistant layers are present in these channels which were not included in the model. It is known that these layers are present in this area, but the exact locations are not known (Van der Spek & van Heteren, 2004). At the Marsdiep (1) and the northern part of the Nieuwe Schulpengat (4) a non-erodable layer is assumed in the model.

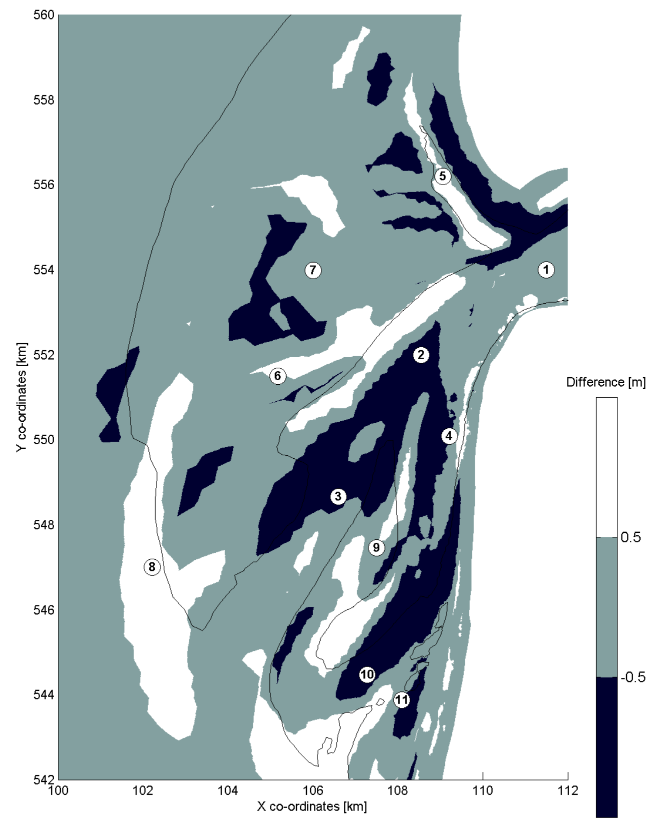

Figure 4. Computed erosion/sedimentation pattern

4.5 *Calibration of the longshore sediment transport, volume change of the ebb tidal delta and sediment import into the Wadden Sea*

In the calibration procedure, also attention is paid to the longshore sediment transport along the coast. In Section 2 the (estimated) actual longshore transport is given. Table 4 summarizes the actual and calculated net transport rates along the coast. The model reproduces the increase in net northward directed sediment fluxes from Petten to Huisduinen quite well, with a tendency to underestimate the longshore transport rate, but given the limited accuracy of the observed volumes the model performs fairly well.

The sediment flux to the Wadden Sea is calculated at 2.4 million m^3 per year. Elias (2006) estimates the sediment import at 5 to 6 million m^3 per year. So the model is underestimating the sediment import to the

Wadden Sea, however the direction of the sediment flux is correct.

The erosion of the ebb tidal delta was established at 3.6 million m^3 per year by Elias et al. (2006). The model calculates an erosion of 1.3 million m^3 per year, an underestimation of the actual volume.

Table 4. Actual and computed annual net longshore sediment transport in northward direction

Coastal position along beach	Actual (m^3/year)	Model (m^3/year)
0 km (Huisduinen)	400,000	300,000
10 km	300,000	175,000
20 km (Petten)	200,000	50,000
30 km (South)	100,000	0

4.6 *Calibration of the beach nourishment volumes*

In the model the beach is maintained every year by refilling the sediment that has eroded from the beach up to the initial beach bathymetry. In this way the model can be used to determine the nourishment volumes. In reality the amount of sand that was nourished to maintain the beach was on average 460,000 m^3 per year for the beach between Camperduin and Huisduinen. The model calculates a nourishment volume of 471,000 m^3/year for this part of the coast (see also Table 6, column 2), which lies very close to the real nourishment volume.

4.7 *Conclusion*

In this section the final result of the calibration procedure is presented. The final parameter settings found in the calibration are given in Table 5. The values are within realistic ranges.

Table 5. Parameter settings of the final calibration

Parameter	value	
Grain size	250	[μm]
Fall velocity	0.015	[m/s]
Roughness (White-Colebrook)	0.01	[m]
Morphological acceleration factor	49.5	[-]
Non erodable layers where relevant		

5 MORPHODYNAMIC RESULTS

5.1 *General*

Using the calibrated model several development schemes were computed. In this chapter only the autonomous development is presented and the effect of the beachheads. Reference is made to Dam & Van Leeuwen (2009) for the results of all of the computations.

5.2 *Autonomous development of the study area over 50 years*

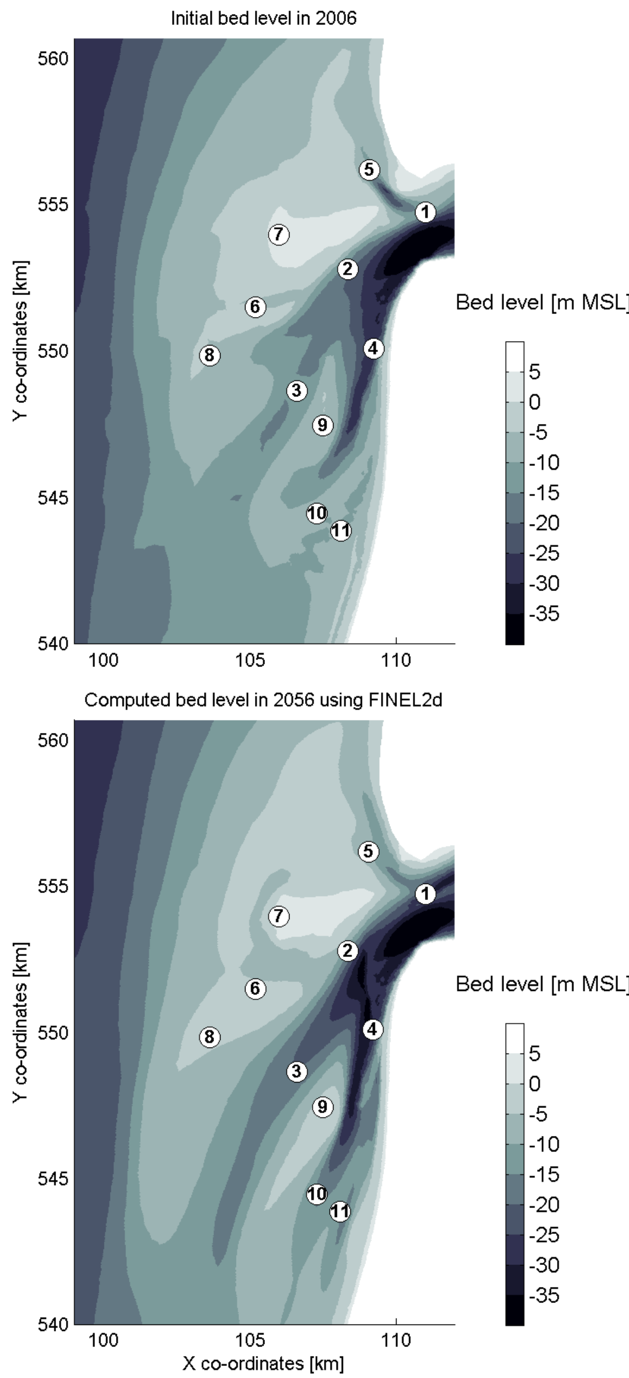

Figure 5. Initial bed level in 2006 and computed bed level in 2056 using FINEL2d

The calibrated model is used to make a prediction of the morphological changes over 50 years, maintaining the beach at its present location. Figure 5 shows the initial bathymetry of 2006 and the calculated bathymetry of 2056. The model results show the direction in which the delta is forming in the next decades, although erosion resistant layers, which are not known exactly can influence the speed of migration.

Several developments can be observed: the migration of the Nieuwe Schulpengat (4 and 10) towards the coast will continue in the coming decades. The onshore migration of the Molengat (5) will also continue and the channel will lose some of its size. The channel the Nieuw Landsdiep (11), which is now only a minor channel will grow in size and will threaten the beach just north of Callantsoog.

The Schulpengat channel (3) will continue to grow.

The southern part of the ebb tidal delta called the Zuiderhaaks (8) will continue to grow in southward direction. Also the delta north of the Noorderhaaks (7) is increasing in size. A new channel between the filed in Westgat (6) and the Noorderhaaks (7) has formed, which is likely to grow further in the decades after this 50 year period.

5.3 *Morphological effect of beachheads*

Since the grid size of this model is small enough to include the individual beachheads a sensitivity calculation is carried out with and without the beachheads. The effect in calculated nourishment volumes can be seen in Table 6

Table 6. Nourishment volumes with and without beachheads

	Beachheads (m^3/yr)	No beachheads (m^3/yr)	Difference (%)
km 0-5	128,000	206,000	+ 60 %
km 5-10	77,000	87,000	+ 13 %
km 10-15	121,000	133,000	+ 10 %
km 15-20	103,000	114,000	+ 10 %
km 20-25	42,000	45,000	+ 6 %
Total	**471,000**	**585,000**	**+ 24 %**

Beachheads on the normal coast (km 5-25), outside of the influence of the channels of the ebb tidal delta, have a protecting effect of 10 - 13 percent on the beach maintenance volume. Near the tidal inlet (km 0-5) the effect of the beachheads, which are present at this location, is more important, since the channel cannot migrate further to the coast. The protecting effect here (km 0- 5) is approximately 60% of the nourishment volume.

6 CONCLUSION

In this paper a high resolution long term process based morphological model of the northern part of the Holland Coast and Texel inlet is presented. Calibration of the model on a 6 year period shows that most of the morphological developments of the ebb tidal delta of the Texel inlet can be reproduced. Net longshore sediment transport rates can be reproduced quite well. Also nourishment volumes which have taken place at the beach are calculated quite well by the model. The model is however underestimating the sediment transport to the Wadden Sea and the continuing erosion of the ebb tidal delta by a factor 2. Knowledge of the erosion resistant layers in the area is necessary to give more accurate predictions of future morphological changes.

The model was used to predict the morphological changes in the coming 50 years. The model shows that the channels of the ebb tidal delta will continue to migrate towards the coast, thereby threatening the coast. The protecting effect of the beachheads at the beach was established at 10-13% less nourishment requirement. Near the ebb tidal delta the protecting effect is higher at 60%.

This model has proven to be a qualitative good model which is a useful tool in decision making processes.

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